SUBMITTED TO APJL ON 21 SEPTEMBER 2006, ACCEPTED 24 OCTOBER 2006
Preprint typeset using LaTeX style emulateapj v. 6/22/04

OBSERVATIONS OF THE 6 CENTIMETER LINES OF OH IN EVOLVED (OH/IR) STARS

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Draft version October 25, 2006

ABSTRACT

Recent observational and theoretical advances have called into question traditional OH maser pumping models in evolved (OH/IR) stars. The detection of excited-state OH lines would provide additional constraints to discriminate amongst these theoretical models. In this Letter, we report on VLA observations of the 4750 MHz and 4765 MHz lines of OH toward 45 sources, mostly evolved stars. We detect 4765 MHz emission in the star forming regions Mon R2 and LDN 1084, but we do not detect excited-state emission in any evolved stars. The flux density and velocity of the 4765 MHz detection in Mon R2 suggests that a new flaring event has begun.

Subject headings: masers — stars: late-type — radio lines: stars — stars: AGB and post-AGB — ISM: individual (Mon R2, LDN 1084)

1. INTRODUCTION

The standard model of the pumping mechanism behind 1612 MHz masers in OH/IR stars was developed by Elitzur et al. (1976). The masers are believed to be pumped by 35 μm radiation, which connects the ground states with the $^2\Pi_{1/2}, J = 5/2$ states. Subsequent decays down the $^2\Pi_{1/2}$ ladder and back to the ground states invert the 1612 MHz transition when the infrared transitions are optically thick. Pumping by 53 μm radiation (via the $^2\Pi_{1/2}, J = 3/2$ states) can also invert the 1612 MHz transition by this mechanism (Elitzur 1981).

More recent detailed modelling by Gray et al. (2005) offers greater insight into 1612 MHz inversion. The two primary ways of pumping the 1612 MHz maser are through collisional excitation within the $^2\Pi_{3/2}$ ladder and radiative excitation by 53 μm photons via the $^2\Pi_{1/2}, J = 3/2$ states, with the latter being the dominant source of the inversion. In the case of a large population transfer through the $^2\Pi_{1/2}, J = 1/2, F = 1^-$ level, it is possible that the 4750 MHz ($F = 1^- \rightarrow 1^+$) and 4765 MHz ($F = 1^- \rightarrow 0^+$) Λ-doubling transitions will be seen in addition to the 1612 MHz transition.

An important detail in these models is whether the radiative pump operates primarily through the 35 μm infrared lines or the 53 μm lines. The former are more energetic and therefore require a larger far infrared radiation field to produce an efficient maser pump. Detailed hot envelope models can include a large contribution from 35 μm radiation (M. D. Gray 2006, private communication). Unfortunately, infrared data are inconclusive as to the relative importance of these pumping routes. An analysis of archive data from the Infrared Space Observatory by He et al. (2005) produced three detections of 35 μm absorption in red supergiants, but also 15 nondetections among stellar objects where the absorption line should be above the threshold of detectability, assuming the Elitzur et al. (1976) pump rates. All sources with detected 35 μm absorption also display 53 μm absorption with similar equivalent widths (He et al. 2005). The authors suggest that 53 μm absorption may play a role in pumping 1612 MHz masers in evolved stars, consistent with Gray et al. (2005).

Detections of OH lines beyond the ground-state transitions could provide useful constraints to clarify the modelling picture. There have been several searches for maser emission in the 4.7 GHz ($^2\Pi_{1/2}, J = 1/2$) and 6.0 GHz ($^2\Pi_{3/2}, J = 5/2$) transitions of OH (Thacker et al. 1970; Zuckerman et al. 1972; Baudry 1974; Rickard et al. 1975; Claussen & Fix 1981; Jewell et al. 1985; Desmurs et al. 2002). All searches failed to detect excited-state emission from OH/IR stars, with the exception of 6035 MHz emission in NML Cyg (Zuckerman et al. 1972) and 4750 MHz emission in AU Gem (Claussen & Fix 1981), neither of which was confirmed in subsequent observations by Jewell et al. (1985). But the total number of observed OH/IR stars in the 4.7 GHz lines remains less than three dozen. Additionally, observers have generally chosen sources with very bright far infrared fluxes, which may include an inherent bias if negative optical depths in the 4.7 GHz lines are not independent of the ratio of 35 μm to 53 μm fluxes.

Given the renewed interest in OH/IR star pumping generated by the He & Chen (2004) and He et al. (2005) observations as well as the Gray et al. (2005) theory, further searches for excited-state OH in evolved stars are justified. In this Letter, we present observations of a larger sample of OH/IR stars and other sources in the 4750 and 4765 MHz lines of OH.

2. OBSERVATIONS

Data were taken during three sessions during 2006 May 25–27 using the Very Large Array (VLA). The observations occurred near the end of reconfiguration between A and BnA configurations. Several antennas were out of the array due to the move as well as the EVLA upgrade, leaving 22 antennas in operation.

The observed sources are drawn primarily from the Chen et al. (2001) catalogue of OH/IR sources and were selected based on their range of observability in LST. Several of these sources are not actually evolved stars, likely due to incorrect IRAS associations at the 1′ level. The total time on each source was approximately three minutes, with one-minute calibrator scans interspersed between sources. A significant amount of radio frequency interference (RFI) was observed on two sources, IRAS 05437–0001 and IRAS 06053–0622, although simple flagging of the affected time

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ranges resulted in sufficient data apparently free of RFI to produce reasonable images.

The 4750.656 and 4765.562 MHz transitions of OH were observed simultaneously in both circular polarizations. The 1.5625 MHz bandwidth was centered at the LSR velocity of each source listed in Table 1 and divided into 128 spectral channels, giving a channel spacing of 12.207 kHz ($0.77\ \mathrm{km\,s^{-1}}$).

Data reduction was performed in the Astronomical Image Processing System (AIPS, Greisen 2003). Image cubes of the central $80\ \mathrm{km\,s^{-1}}$ and measuring $10'$ in Right Ascension and Declination were created using IMAGR. Each channel was visually scanned for maser emission and analyzed for the maximum pixel value and rms noise. Detections and upper limits for nondetections are listed in Table 1.

The snapshot observations provided a single-channel rms noise of ~ 20 mJy, which would allow for a 5σ detection of a 100 mJy maser source. This is the flux density of the lone detection of a 4.7 GHz maser in the Mira variable AU Gem (Claussen & Fix 1981). The distance of this star, 2.4 kpc (Nguyen-Q-Rieu et al. 1979), is typical for our sample.

3. RESULTS

3.1. *Detections*

There were no detections among the OH/IR stars, but two previously known 4765 MHz masers were observed in star forming regions. The first of these sources, IRAS 21413+5442 (LDN 1084), is a region of massive star formation affiliated with an ultracompact H II region (Cohen et al. 1988). From our observations, the detected maser has a flux density of 250 mJy in the channel centered at $-61.80\ \mathrm{km\,s^{-1}}$ and 260 mJy in the channel centered at $-62.57\ \mathrm{km\,s^{-1}}$. The data are consistent with a single point source at a velocity near $-62.2\ \mathrm{km\,s^{-1}}$ and located at $21^{\mathrm{h}}43^{\mathrm{m}}01^{\mathrm{s}}.452, +54^{\circ}56'17''.87$ (J2000). This agrees with the position of the $-62.10\ \mathrm{km\,s^{-1}}$ feature detected by Harvey-Smith & Cohen (2005) to within $0''.25$. The second detected source is IRAS 06053–0622, (Mon R2). Its flux density is approximately 2.5 Jy in the channel centered at $10.4\ \mathrm{km\,s^{-1}}$, located at $06^{\mathrm{h}}07^{\mathrm{m}}47^{\mathrm{s}}.845, -06^{\circ}22'56''.61$, which agrees to within $0''.08$ with the position of the brighter $10.62\ \mathrm{km\,s^{-1}}$ maser detected by Harvey-Smith & Cohen (2005).

Because the width of the channels used during the observations is larger than a typical maser width in a star forming region, the quoted flux densities are lower limits. A closer approximation can be found by dividing the channel width by the estimated velocity range of the maser and then multiplying by the observed flux density. Assuming a single maser whose linewidth is $0.4\ \mathrm{km\,s^{-1}}$ (an average value for Mon R2; see Smits et al. 1998) yields flux densities of just under 1 Jy for LDN 1084 and 5 Jy for Mon R2.

3.2. *Variability*

As is common for masers, both LDN 1084 and Mon R2 have displayed a certain degree of variability in the past. The flux density of the 4765 MHz maser in LDN 1084 was observed to be 700 mJy in 1989 and again in 1991 (Cohen et al. 1991, 1995) but had dropped to 480 mJy by 1995 (Harvey-Smith & Cohen 2005). Our data suggest that the maser flux density has since increased. The velocity of this feature, $-62.1\ \mathrm{km\,s^{-1}}$, is in the middle of the range of 6035 MHz emission (Fish et al. 2006) and is consistent with our measurements given our coarse spectral resolution.

In Mon R2 4765 MHz emission was first detected at $10.9\ \mathrm{km\,s^{-1}}$ by Gardner & Martín-Pintado (1983). Cohen et al. (1995) confirmed its status as a maser and noticed variability, with a peak flux of 1.5 Jy in 1990. Subsequent monitoring caught two flares to a maximum of nearly 80 Jy, with the central maser velocity varying between about 10.55 and $10.85\ \mathrm{km\,s^{-1}}$ (Smits et al. 1998; Smits 2003). In 2000, Dodson & Ellingsen (2002) failed to detect any 4765 MHz emission in Mon R2 at the 80 mJy level, and Smits (2003) found no 4765 MHz emission in Mon R2 between 1998 December and the end of their observations in 2001 November despite monitoring the source at two-week intervals.

It appears that emission from the 4765 MHz maser(s) in Mon R2 has returned. The LSR velocity of our detection is consistent with being near or just below the low end of the aforementioned velocity range. We detect strong emission in the channel centered at $10.44\ \mathrm{km\,s^{-1}}$ and possible weak emission in the next-lower velocity channel ($9.67\ \mathrm{km\,s^{-1}}$), but not in the next-higher channel ($11.20\ \mathrm{km\,s^{-1}}$).

4. DISCUSSION

We do not detect 4.7 GHz OH maser emission from any of the evolved stars in our sample. This is consistent with most previous surveys of evolved stars, in which no excited-state emission is detected (Thacker et al. 1970; Baudry 1974; Rickard et al. 1975; Jewell et al. 1985; Desmurs et al. 2002). Nevertheless, excited-state emission *has* been detected in two evolved stars. Zuckerman et al. (1972) report on 6035 MHz (and possibly 6030 MHz) maser emission in the red supergiant NML Cyg, although not at the same velocity as the 1612 MHz masers. Likewise, Claussen & Fix (1981) report on 4750 MHz emission from the Mira AU Gem; again the velocities are not the same as in ground-state emission, although the authors note that the spectrum of the 4750 MHz emission appears to be centered at the same velocity, with peaks nearer the central velocity than at 1667 MHz. Both of these appeared to be convincing detections, yet the 6035 MHz emission in NML Cyg has disappeared (Jewell et al. 1985; Desmurs et al. 2002). The 4750 MHz emission in AU Gem was also not redetected in observations by Jewell et al. (1985), although the 100 mJy maser would only have been 1.5 times their rms noise, which does not conclusively establish that the maser had disppeared. Nevertheless, it appears that excited-state emission in late-type stars is both rare and time-variable.

There are several classes of theoretical models for OH pumping in circumstellar shells. The Elitzur et al. (1976) model of pumping via the 35 μm lines and subsequent decay down the $^2\Pi_{1/2}$ ladder inverts the 1612 MHz line. Pumping via the less-energetic 53 μm lines can also produce a strong 1612 MHz inversion (Elitzur 1981; Gray et al. 2005). Collisions may contribute a substantial fraction of the inversion (Gray et al. 2005). Far infrared line overlaps can invert the 1612, 1665, and 1667 MHz lines because of asymmetries in the dipole matrix elements (Bujarrabal et al. 1980a,b). Near infrared line overlap, possibly with H_2O, also may be necessary to account for main-line maser emission (Cimerman & Scoville 1980; Collison & Nedoluha 1993, 1994).

A combination of several of these pumps may occur in evolved stars, either in the same spatial region or at different radii. Observational evidence supports several of these pumping models. Multiple infrared lines of OH have been detected (Sylvester et al. 1997; He & Chen 2004; He et al. 2005). Interferometric measurements indicate that main-line masers exist at smaller radii than 1612 MHz masers in circumstellar envelopes (Harvey et al. 1974). Substantial qualitative differences in variability confirm this (Etoka & Le Squeren 2000) and likely indicate that dust reprocessing of radiation is a critical element of the radiative pumping (Elitzur 1978). The spectrum of the lone 4750 MHz detection in AU Gem also suggests that the right conditions for masing in excited-state lines exist interior to the region producing main-line masers (Claussen & Fix 1981). This is analogous to H_2O and 1612 MHz OH maser observations in other stars, in which the H_2O masers are typically seen at smaller expansion velocities than the OH masers and are observed to exist at smaller radii as well (Habing 1996).

Why, then, are excited-state masers in late-type stars so rare? Three ingredients are essential to produce a detectable OH maser: a sufficient column density of OH, velocity coherence, and effective pumping conditions. The abundance of OH masers in the envelopes of evolved stars clearly shows that column density of OH is sufficient to produce maser activity. But velocity coherence may be a problem in the excited states. It appears that 4750 MHz masers are located at smaller radii than 1612, 1665, and 1667 MHz masers. It is possible that the velocity field at this radius is too irregular to support large coherent path lengths, due possibly to accelerations or turbulence.

It is also possible that the conditions necessary to pump excited-state masers are very fragile. Many pairs of far infrared OH transitions overlap at different Doppler shifts on the order of several km s^{-1} (see Table 2 of Collison & Nedoluha 1993). Small changes in the velocity structure of a circumstellar envelope may therefore have large consequences in the pumping. When combined with other pump mechanisms, such as collisional excitation, these effects may be exaggerated. Detailed modelling including the effects of multiple pump mechanisms may be required to discover the precise physical conditions responsible for producing detectable excited-state maser emission.

More observations will be required in order to understand the narrow range of parameter space conducive to excited-state OH pumping. In particular, the two late-type stars in which excited-state maser emission was detected in one epoch (NML Cyg at 6035 MHz and AU Gem at 4750 MHz) should be reobserved with greater sensitivity. If they are redetected, their variability and spatial distribution will provide important clues as to the pumping mechanism responsible for excited-state maser emission in evolved stars.

The National Radio Astronomy Observatory is a facility of the National Science Foundation (NSF) operated under cooperative agreement by Associated Universities, Inc. L. K. Z. acknowledges support from the NSF Research Experiences for Undergraduates (REU) program. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

Facility: VLA

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TABLE 1
RESULTS OF OBSERVATIONS AT 4750 AND 4765 MHZ

IRAS Name	RA[a]	Dec[a]	Source Type[b]	Name	Alias	RAFGL Name	v_{LSR}[a]	Flux Density[c]		Source Type Refs
	(J2000)						(km s^{-1})	4750 (mJy)	4765	
00170+6542	00:19:51.5	+65:59:31	OH/IR	···	OH 119.7+3.3		−51.3	<77	<82	1
00428+6854	00:46:00.6	+69:10:54	Mira	V524 Cas	IRC +70012	107	−25.5	<76	<80	2
01037+1219	01:06:25.9	+12:35:54	OH/IR	WX Psc	IRC +10011	157	8.8	<81	<86	3
01085+3022	01:11:15.9	+30:38:05	Mira	AW Psc	IRC +30021	168	−26.8	<84	<93	3
01110+2652	01:13:47.8	+27:07:56	SR	RT Psc	IRC +30023	179	−116.4	<90	<94	4
01304+6211	01:33:50.6	+62:26:47	Mira	V669 Cas	OH 127.8+0.0	230	−55.0	<78	<82	5
01572+5844	02:00:44.1	+58:59:03	OH/IR	···			−11.4	<77	<82	6
02192+5821	02:21:51.1	+58:35:08	OH/SG	S Per	IRC +60088	323	−38.5	<83	<87	7
02420+1206	02:44:45.0	+12:19:00	Mira	RU Ari			19.8	<82	<86	2
02547+1106	02:57:27.2	+11:18:04	OH/IR	YZ Ari		5087	15.6	<82	<86	3
03206+6521	03:25:08.5	+65:32:05	OH/IR	···	OH 138.0+7.2		−37.5	<104	<76	6
03293+6010	03:33:30.5	+60:20:09	OH/IR	···	OH 141.7+3.5	5097	−57.5	<77	<82	1
03507+1115	03:53:28.6	+11:24:20	Mira	IK Tau	IRC +10050	529	33.9	<82	<106	8
04130+3918	04:16:24.6	+39:25:44	Carbon	C* 192		6312	−5.7	<72	<91	9
04396+0647	04:42:21.5	+06:52:39	OH/IR	BZ Tau	IRC +10068	619	18.2	<81	<102	3
04505−1006	04:52:57.7	−10:02:00	OH/IR	EY Eri			17.1	<77	<98	10
04575+1251	05:00:23.9	+12:56:06	OH/IR	···	OH 187.7−17.6	5134	0.9	<76	<100	1
05274+3345	05:30:45.6	+33:47:52	SFR	···		5142	−4.1	<70	<74	11
05358−0704	05:38:18.8	−07:02:27	FU Ori	V883 Ori		4433S	5.3	<84	<103	12
05373−0810	05:39:42.6	−08:09:08	Carbon	V1187 Ori	IRC −10095	796	11.2	<81	<103	13
05380−0728	05:40:27.7	−07:27:28	FU Ori	Reipurth 50	HBC 494	5163	3.9	<81	<102	12
05423+2905	05:45:29.7	+29:07:04	OH/IR	V530 Aur			28.7	<77	<84	6
05437−0001	05:46:17.8	−00:00:17	SFR	LDN 1627	M 78		13.1	<100	<130	14
06053−0622	06:07:46.7	−06:23:00	SFR	Mon R2		877	8.9	<120	2500[d]	15
06297+4045	06:33:14.9	+40:42:50	OH/IR	···	IRC +40156	955	−16.0	<77	<83	10
06319+0415	06:34:37.6	+04:12:44	(P)PN	Rosette		961	12.7	<90	<111	5
06500+0829	06:52:46.9	+08:25:20	OH/IR	GX Mon	IRC +10143	1028	−10.7	<70	<93	16
07209−2540	07:22:59.2	−25:46:08	OH/SG	VY CMa	IRC −30087	1111	22.4	<75	<83	7
07331+0021	07:35:41.2	+00:14:59	(P)PN	AI CMi		5236	28.4	<76	<83	17
07399−1435	07:42:17.1	−14:42:50	(P)PN	QX Pup	OH 231.8+4.2	5237	15.9	<76	<81	18
07445−2613	07:46:37.8	−26:20:34	Mira	SS Pup	OH 242.4−0.7	1192	82.7	<76	<82	16
07585−1242	08:00:50.6	−12:50:31	Mira	U Pup	IRC −10184	1215	−15.6	<75	<81	16
08005−2356	08:02:40.6	−24:04:43	(P)PN	V510 Pup			−0.1	<87	<75	19
08357−1013	08:38:08.8	−10:24:17	OH/IR	···	OH 235.3+18.1	1274	17.8	<72	<76	10
09429−2148	09:45:17.0	−22:01:56	OH/IR	IW Hya	IRC −20197	5259	39.0	<75	<78	10
21413+5442	21:43:01.4	+54:56:16	SFR	LDN 1084			−61.8	<83	260[d]	20
21554+6204	21:56:58.3	+62:18:43	OH/IR	GLMP 1048			−21.4	<75	<77	6
22176+6303	22:19:18.2	+63:18:46	SFR	S140		2884	−7.0	<96	<81	8
22177+5936	22:19:27.9	+59:51:21	OH/IR	···	OH 104.9+2.5	2885	−24.9	<76	<77	1
22466+6942	22:48:14.2	+69:58:29	OH/IR	V708 Cep			−45.9	<79	<81	6
22525+6033	22:54:32.0	+60:49:38	OH/SG	MY Cep		2987	−0.8	<79	<81	7
22556+5833	22:57:41.3	+58:49:15	Symb	V627 Cas	HBC 316	2999	−49.5	<74	<77	21
23352+5834	23:37:40.1	+58:50:47	Mira	V850 Cas			−0.1	<77	<92	22
23416+6130	23:44:03.6	+61:47:22	OH/SG	PZ Cas	IRC +60417	3138	−38.5	<63	<65	7
23425+4338	23:45:02.1	+43:55:22	OH/IR	EY And	IRC +40545	3143	−42.5	<84	<88	10

REFERENCES. — (1) Le Squeren et al. (1992); (2) Szymczak & Le Squeren (1999); (3) Lewis (2000); (4) Jura & Kleinmann (1992); (5) He et al. (2005); (6) Galt et al. (1989); (7) Lewis (1991); (8) He & Chen (2004); (9) Cohen et al. (1996); (10) Lewis (2001); (11) Snell et al. (1988); (12) Strom & Strom (1993); (13) Szczerba et al. (2002); (14) Parker (1991); (15) Knapp & Brown (1976); (16) Sivagnanam et al. (1988); (17) Omont et al. (1993); (18) te Lintel Hekkert et al. (1988); (19) Slijkhuis et al. (1991); (20) Cohen et al. (1988); (21) Kolotilov et al. (1996); (22) Sivagnanam et al. (1990)

[a]Pointing center and central LSR velocity of observations, taken from the Chen et al. (2001) catalogue.

[b]Carbon: Carbon Star; OH/SG: OH/Supergiant; (P)PN: (Proto)-Planetary Nebula/post-AGB star; SFR: H II Region/Star Forming Region; SR: Semiregular Variable; Symb: Symbiotic. Note that the status of several sources is disputed and that not all categories are mutually exclusive.

[c]Upper limits are 4σ.

[d]Detected flux density in a single channel of effective resolution 0.92 km s^{-1}. See §3.1 for a discussion of likely maser width and peak flux density. The maser in Mon R2 was detected in the channel centered at 10.4 km s^{-1}.